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10

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AUDIO FREQUENCY STANDARDS

by B. J. Simpson

INTRODUCTION

It comes as a surprise to many people working in the audio field that there are so few standards of performance to guide them. The result of this is that it is, for example, very difficult to define the widely-used term "high fidelity". And in the absence of an acceptable definition for this term, which would of necessity embrace certain minimum standards of performance in order to mean anything, the term is ambiguous. Like all such terms, "high fidelity" can be interpreted to mean almost anything within reason that the user wishes.

This is illustrated, not only in the very wide use of the term, but in some cases in the type of equipment to which it is applied. Whilst the concept of high fidelity must at least mean something possessing a high standard, this is not always displayed by the equipment to which it is applied.

The very fact that no precise definition is available leads to divergences of opinion. The layman, or the person with only limited technical knowledge, frequently becomes completely confused when he compares all the different statements he has heard from dealers, friends and "experts."

How much better would it be were he able to obtain complete specifications on the units he is considering and compare them detail by detail? I have in mind a model specification issued by a leading maker of pickups. His specification is complete in every detail one could wish; there is left absolutely no doubt as to what is claimed; his reputation is such that his figures are accepted without question.

There can be little doubt that some of the disparity of views arises from the fact that dealer A may be particularly interested in brand X, whilst dealer B may handle brand Y. With most types of merchandise, the intended buyer is able to arm himself with brochures full of technical and other data, take the whole lot home, and spend the next few evenings happily going over the market and making up his mind. There is of course also the point that many items that he buys are much less complex than the type of apparatus we are now discussing, and the number of choice factors is consequently reduced, or subject to a smaller number of variables and imponderables.

Much of the rest of the trouble certainly arises from two main causes, which are themselves to some extent related. The first and most obvious reason is the absence of well-defined standards of performance, with the application of a precise nomenclature to describe the categories of performance standards into which various units of equipment fall.

In the absence of such standards or yardsticks, there is no alternative but to fall back upon the individual specifications, and endeavour to compare them. It is here that the second major source of trouble is found. This type of difficulty may itself be subdivided again into two main components. It must here be remembered that a technical specification, in order to mean anything at all, must state not only the performance obtained, but the conditions under which the measurements of that performance were obtained.

Many so-called technical specifications offered today mean little when they are examined critically. Either the statement of performance is incomplete, or the conditions of measurement are not stated, or both. This makes evaluation of a unit, and comparison with other units, very difficult if not impossible.

SPECIFYING PERFORMANCE

The remarks in the foregoing paragraphs are critical, and are intentionally so. It will be shown later that the electronics industry, as represented by those manufacturers manufacturing audio equipment, realise the problems. Measures taken by them to improve the status quo will also be explained. But before we go on to those subjects, let us see how some of the more critical remarks already made can be substantiated.

It will be understood that actual cases cannot be mentioned, but cases typical of those to be described here can be found any day in "hi fi" literature. We will assume that we are studying a brochure for a pickup. One of the items we are naturally interested in is the frequency response, and on looking down the list of impressive-looking technical data, we find the response given as "30-15,000 cps"; this is all that is given. At first sight, this looks very encouraging, and leads to a warm glow in the intended purchaser.

But before he builds castles in the air around the prospect of attaching this unit to his system, the balloon is punctured, if he stops to think. Does this mean 30 to 15,000 cps ± 3 db, as one might perhaps expect? Or does it mean only what it says it means, that there is *some* response over the frequency range stated? This is a simple case, and it cannot be denied that a reputable manufacturer, even if loose in specifying technical data, will still provide a pickup of good quality for the money paid. The point I wish to make is that it would be a simple thing to make a statement that does mean something. Not only would this inevitably put the maker into a better light, but it would protect his product against inferior competition, and would also tell the buyer precisely what he is getting.

Cases of the kind quoted are very frequent, and very few seem to be entirely blameless in this regard. That was a case of imperfect specification. Let us go on to have a look at what happens when the conditions of measurement are not stated. The frequency response of an amplifier is often checked at the 1 watt level into a resistive load; does this response still hold good at full rated power output? Lots of power amplifiers work well at the 1 watt level, but considerably fewer have a comparable performance at the full rated output. Take distortion, one of the most important statements; this is customarily measured at either 400 or 1,000 cps. Frequently however, and particularly in high grade units, distortion is also measured at 50 cps or some other low frequency. This imposes a much more severe test on the amplifier.

A similar examination of entire specifications could be made, but the point has probably been made by now, and we can go on to other things. Firstly it will be necessary to show to what extent the industry is aware of these problems, and to describe those measures that have been taken so far to remedy the situation. It must be pointed out however that such standards as are already available are not in universal use, but are subscribed to by certain groups of manufacturers only.

AVAILABLE STANDARDS

It was previously mentioned that performance standards require two things, measurement of the performance and a statement of the conditions under which the measurements were made. As far as I am aware at this time, efforts to introduce minimum performance standards have been unsuccessful, but there have been two useful moves towards the complementary step of establishing standardisation of measurement techniques. This means that provided the equipment is manufactured by a manufacturer within one of two present groups, the conditions of measurement are known.

The two groups referred to here are the Institute of High Fidelity Manufacturers Inc., of New York, and the Audio Manufacturers' Group of the British Radio Equipment Manufacturers' Association. The former issued in September 1959 a Specification IHFM-A-200, entitled "IHFM Standard Methods of Measurement for Amplifiers". This specification, as the title implies, is concerned entirely with the standardisation of measurement methods; no effort is made to indicate any minimum standards of performance. Such a specification is however a major step towards a rationalisation of the position.

The British specification is of much later date. The final specification was issued in April of this year, and followed the distribution of a draft specification for comment and discussion in March 1960. Here again, the document deals with measurement methods and methods of expressing the results. At the same time, several interesting clauses that appeared in the original draft, particularly those related to suggested minimum performance figures, were entirely deleted in the final copy. More will be said of these later.

The full title of the A.M.G. Specification is "Specification for Methods of Measuring and Expressing the Performance of Audio Amplifiers". Whilst neither of the two specifications attempts to lay down any specific performance standards, it is interesting to note that a certification scheme has been introduced by the A.M.G. coincident with the release of their specification.

Under this scheme, a certificate is issued for the purpose of registering equipment where the performance claimed by the maker has been tested and verified under conditions laid down in the specification. The testing is carried out by an independent testing house and certificated to the A.M.G., who then register the equipment and issue certification labels for use on the equipment.

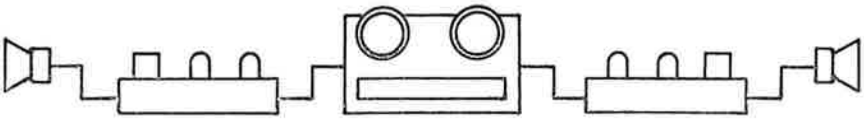
This means that we may expect to see within the reasonably near future British equipment bearing this seal of approval. It must however be remembered that this is only a certification that the unit does what the maker claims, not that the actual performance is up to a certain standard. Where an amplifier bears the seal, at least we will know how the measurements were taken, and will be able to interpret them in a knowledgeable way.

PERFORMANCE STANDARDS

It has been stated that the two specifications already mentioned are not concerned with actual performance, but only in the method of measuring performance. At the same time their contribution does in fact go a little beyond this. Both specifications, for example, call for a preamplifier to be terminated during test in a load of 100K ohms with 1,000 pf in parallel, unless otherwise specified by the maker. This will ensure satisfactory operation when connected to a following unit.

As far as power output is concerned, the A.M.G. still adhere to the rms or continuous sine wave output, measured into the load, whilst the IHFM use the music power output rating previously mentioned in these pages. As one may expect, the two specifications are very similar in many respects. Neither of them has included the measurement of transient testing (square waves) or intermodulation distortion, on the grounds that the methods of testing amplifiers for these characteristics have not progressed to the point where a generally-acceptable method can as yet be laid down. This is a pity, as it is generally acknowledged today that now that we have amplifiers with very low orders of harmonic distortion, and are striving for better things, intermodulation distortion can in some circumstances be more objectionable than harmonic distortion.

One very useful test called for in the A.M.G. document is one for stability. The test consists of operating the amplifier with a capacitive load varied from 0.01 mfd to 0.1 mfd in 0.01 steps, and thence to 1.0 mfd in 0.1 steps. Under this test the amplifier must be unconditionally stable if so claimed by the maker. Alternatively, the maker may claim that the amplifier is stable under normal conditions, in which case the capacitor becomes a fixed value which has the same impedance at 200 Kc as the nominal output impedance of the amplifier, e.g., for a 15-ohm output, the capacitor value would be 0.05 mfd. This condition is intended to simulate the worst conditions of capacitive loading likely to be met with in a domestic installation.



A.M.G. PROVISIONAL STANDARDS

It has already been stated that the original draft of the A.M.G. specification contained much more than methods of test. Although these clauses have now been deleted from the final specification, it may be interesting to look them over, as by inference at any rate, they could be said to represent thinking on the matter of performance standards in early 1960 when the draft copy was first released. It must be made quite clear that these matters are not now operative, and are mentioned here solely for discussion.

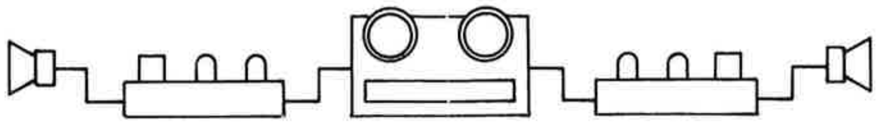
In the first place, there was the conception of two grades of amplifier, group A and group B. A group A amplifier had a rated power output of not less than 10 watts (5 + 5 watts for stereo), and a group B amplifier an output of not less than 5 watts (2.5 + 2.5 watts for stereo). Both groups were required to have an input sensitivity for full output of between 100 and 1,000 millivolts.

Turning now to harmonic distortion, group A amplifiers were required to have a total harmonic distortion not greater than 0.1% at 1,000 cps, and not greater than 0.5% at 40 cps and 15 Kc. The corresponding figures for a group B amplifier were 1.0% at 1,000 cps, and 3.0% at 70 cps and 10 Kc. Group A amplifiers were required to have a frequency response ± 1 db from 20 cps to 20 Kc, measured at one quarter of the rated power output, and ± 1 db from 40 cps to 15 Kc at the full rated power output. Group B amplifiers were expected to reach the same performance over ranges of 40 cps to 15 Kc, and 70 cps to 10 Kc, respectively.

Hum and noise form an important subject, as nothing can be more annoying in an otherwise good amplifier. Group A amplifiers were expected to be between 75 and 85 db down on full output, depending on the stated input sensitivity between 100 and 1,000 millivolts. The figures for group B were 70 to 80 db.

These were the more important figures put up at the time for discussion. It is understandably difficult to reach standards of performance acceptable to a wide range of manufacturers, and this is doubtless why these proposals were dropped in the final release. It could also be argued that some of the few requirements mentioned here were of an unnecessarily high standard for general use, and may tend to put the equipment up into a remote class economically. This brings up again the old argument between ideals and practicality, and can only be decided by the individual.

It is noted though that few manufacturers, either in Britain or in the U.S.A. produce amplifiers that would have met the group A requirements, and those that approach the figures are not cheap. It would probably be a fair approximation to say that once an amplifier is down to 1% total distortion or less, the added cost of



making further improvement probably follows a square law. It must also be remembered that the amplifier is required to work with other parts of the system that will inevitably possess poorer performance characteristics; it is well recognised that the weak link in the audio system as we know it today is certainly not the amplifier.

SUMMARY

It has been shown that there is a great need for some type of standardisation in the testing and specification of audio equipment. The standardisation should ideally consist of two complementary measures, the setting up of standards of performance and the setting up of standards of measurement techniques. The situation is aggravated by the fact that in the absence of such standards, apparatus is frequently described by so-called specifications of performance which are incomplete or even meaningless.

It has been shown that two groups of manufacturers, one in Britain and one in the U.S.A., have taken the first step towards clarifying the position by adopting standard measurement techniques. The adoption of minimum standards of performance is still to come.

It appears that the U.S.A. standard is largely used as an internal standard by makers. It is not widely publicised by them, nor do they make it quite clear whether they are members or not in their advertisements. It is probably safe to assume that most of the reputable manufacturers are in fact members, and subscribe to and use the testing specification. It is however difficult for anyone outside the industry to be certain on this point, or in fact to be aware of the specification at all.

In the case of the standard of test procedures published in Britain, it is expected that the existence of the specification will be widely advertised, and the certification scheme, under which apparatus will carry an appropriate label, will ensure that the buyer knows that the equipment not only attains the performance claimed, but that it does so under standard conditions, which are themselves designed to lift the general standard as far as possible.

Because of the interest in, and importance of, the A.M.G. specification, we are reprinting the entire specification as an appendix to this article. Besides indicating the required testing standards, the document will serve as a useful indication to many readers on test techniques in general.

APPENDIX

SPECIFICATION FOR METHODS OF MEASURING AND EXPRESSING THE PERFORMANCE OF AUDIO FREQUENCY AMPLIFIERS APRIL 1962

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1. SCOPE

This specification covers equipment employing valves, transistors, or a combination of both, for sound amplification, but excludes the signal generating source (e.g. gramophone pickup, microphone or tape deck) and the loudspeaker(s).

Where appropriate, separate methods have been laid down for measurements on (*a*) pre-amplifiers, (*b*) power amplifiers and (*c*) integrated amplifiers (i.e. with both the pre-amplifier and power amplifier constructed as one unit.

2. EXPRESSING PERFORMANCE

The performance characteristics of amplifiers should always be quoted with reference to the results achieved at the output voltage or power called for in this specification: if no particular level is specified, this should be the continuous rated output voltage or power (see Clauses 4.2 and 4.3).

3. STANDARD CONDITIONS OF MEASUREMENT

Standard test conditions shall be maintained for all tests, except as otherwise specified.

3.1. **Supplies for Mains-operated Amplifiers**

3.1.1. *Normal supply voltages*

The supply voltage to the amplifier shall be within ± 2% of the rated supply voltage.

If a range of supply voltages is specified (e.g. 220-230 V) the arithmetic mean of the voltages specified for this range shall be used as the rated supply voltage.

3.1.2. *Supply Frequency*

The frequency of the mains supply shall be within ± 2% of the lowest supply frequency for which the amplifier is rated.

3.1.3. *Purity of the mains supply*

The mains supply voltage waveform shall be sinusoidal with less than 2% harmonic content.

3.1.4. *DC supplies*

For dc supplies, the rms value of the ripple shall not exceed 5%.

3.2. **Normal Supply Voltages for Battery-operated Amplifiers**

The type and rated voltage, as specified by the manufacturer, shall be used.

NOTE: If the amplifier is intended for use from either mains or batteries, the measurements should be made when using each of the sources of power in turn as specified in Clauses 3.1 and 3.2.

3.3. **Input and Output Terminations**

3.3.1. The input terminals of the amplifier shall be fed from a source with an output impedance of 10,000 ohms, unless an input impedance is specified by the manufacturer, in which case this value should be employed.

3.3.2. The output terminals of power or integrated amplifiers shall be connected to a non-inductive load resistor which should not vary from the value specified by the manufacturer by more than 5%; this resistance may, wholly or in part, be formed by measuring apparatus.

3.3.3. Amplifiers intended to supply signal voltages to the input circuit of a subsequent amplifier shall be terminated by a load consisting of a 0.1 megohms ± 5% resistor shunted by a 1,000 pf ± 5% capacitor, unless otherwise specified by the manufacturer.

3.3.4. An amplifier intended for simultaneously supplying signal power for loudspeakers and a signal voltage to a subsequent amplifier shall be tested with both loads, as specified in Clauses 3.3.2 and 3.3.3.

3.4. **Measurement Signal**
Unless otherwise specified, a 1,000 cps ± 2% signal shall be used, and shall be sinusoidal with the rms total of all components, other than the fundamental, less than 20% of rated harmonic distortion of the amplifier to be tested, at the level of measurement. A bandpass filter should be inserted to achieve this level, where necessary.

3.5. **Earthing**
Earthing terminals, when provided, shall be connected to earth.

3.6. **Operating Temperature**

3.6.1. *Amplifiers using valves*
The amplifier shall be pre-conditioned by operating for at least 1 hour in the normal operating position, with covers in place and in the cabinet or case resulting in the highest operating temperature where alternatives are available. The measurements shall be taken immediately after removal from the cabinet or case.
The ambient temperature at which the pre-conditioning and measurements take place shall be normal room temperature, i.e. 20° C.

3.6.2. *Amplifiers using transistors* (Class A and Class B output Stages)

3.6.2.1. The amplifier shall be pre-conditioned by operating for 2 hours in the normal operating position, with covers in place, and in the cabinet or case resulting in the highest operating temperature where alternatives are available.

3.6.2.2. During this period a 1,000 cps input, adjusted to deliver 20% of the rated output, shall be applied.

3.6.2.3. The measurements shall be taken immediately after removal from the cabinet or case.

3.7. **Connection of Mains Lead**
If the mains connector is reversible and the leads are uncoded, it shall be connected in the sense which gives the lower measured level of hum when the highest gain input is employed, and shall not be changed for any other test.

3.8. **Controls**

3.8.1. *Gain control*
All controls whose primary function is the adjustment of gain shall be set for maximum gain for the particular input in use, unless it is necessary to take measurements at a reduced gain, when the extent of the gain reduction shall be recorded.

3.8.2. *Tone controls or filters*
Tone controls or filters whose primary function is adjustment of frequency response shall be set or switched to the indicated flat response position.

3.8.3. Controls that vary both gain and frequency response, such as loudness controls, shall be set at the position of flattest frequency response.

3.8.4. Automatic controls actuated by signals within the system and which may be switched in or out by the user shall be rendered inoperative.

3.9. **Stereophonic Amplifiers**

3.9.1. The balance control, with stereophonic amplifiers, shall be set at its indicated balanced position. If separate gain controls are provided for the two channels, they shall both be set for maximum gain for the particular input in use unless it is necessary to take measurements at a reduced gain, when they shall both be turned down to the same extent.

3.9.2. All measurements shall be taken separately for each of the channels in a stereophonic amplifier in turn.

4. DEFINITIONS AND METHODS OF MEASUREMENT

4.1. **Harmonic Distortion**

4.1.1. *Definition*
Harmonic distortion is that part of non-linearity distortion consisting of sinusoidal components whose frequencies are integral multiples of the frequency of the sinusoidal excitation.

4.1.2. *Method of measurement*

4.1.2.1. The amplifier shall be operated under Standard Conditions of Measurement (Clause 3), except as stated below.

4.1.2.2. To ascertain the output voltage or power at which the distortion becomes a specified value, a distortion percentage meter, which automatically sums the power in all the harmonics and gives the result as a percentage of output voltage, may be used, with, if necessary, a high-pass filter to remove hum. Alternatively, a wave analyzer may be employed which measures the value of the individual harmonics from which the total value can then be calculated.
Where a single figure of harmonic distortion is quoted, this shall be for a frequency of 1,000 cps.

4.1.2.3. If it is desired to plot the characteristic curve for harmonic distortion, the amplitude of the input signal shall be adjusted so that the amplifier output is maintained at the level of the rated output voltage or power, as appropriate (Clauses 4.2 and 4.3), while the frequency of the input signal is varied between the upper and lower limits where the measured harmonic distortion in the amplifier output is five times the value claimed by the manufacturer for a frequency of 1,000 cps.
Measurements shall be taken at sufficient intermediate frequencies, including 1,000 cps, to enable the characteristic curve to be plotted, using a logarithmic scale for frequency as the abscissa and a linear scale for distortion as the ordinate.

4.2. **Rated Output Voltage** (of a pre-amplifier)

4.2.1. *Definition*

The rated output voltage is the output voltage claimed by the manufacturer. It is determined by the rms voltage developed across the stated load resistance (Clause 3.3.3.) at a frequency of 1,000 cps, without exceeding the harmonic distortion claimed by the manufacturer.

NOTE: The significance of this figure should be assessed in conjunction with the harmonic distortion characteristic as obtained under Clause 4.1.2.3.

4.2.2. *Method of Measurement*

4.2.2.1. The amplifier shall be operated under Standard Conditions of Measurement (Clause 3).

4.2.2.2. To verify the *rated* output voltage, an input signal at a level to produce the claimed rated output voltage shall be applied to the amplifier, and the level of harmonic distortion shall be measured (using the procedure of Clause 4.1.2.2.) to ensure that its level does not exceed that claimed by the manufacturer.

4.2.2.3. If it is desired to measure the *actual* output voltage (which will usually differ from the *rated* output voltage) the input voltage applied to the amplifier shall be increased until the level of harmonic distortion claimed by the manufacturer (as measured in Clause 4.1.2.2.) is produced in the voltage across the stated load resistance. The rms voltage across the load shall then be measured: this is the *actual* output voltage of the amplifier under test.

4.3. **Rated Output Power** (of a power amplifier or integrated amplifier)

4.3.1. *Definition*

The rated output power is the output power claimed by the manufacturer. It is determined by the power which the amplifier is capable of dissipating continuously in the stated load resistance (Clause 3.3.2.) at a frequency of 1,000 cps, without exceeding the harmonic distortion claimed by the manufacturer.

NOTE: The significance of this figure should be assessed in conjunction with the harmonic distortion characteristic as obtained under Clause 4.1.2.3.

4.3.2. *Method of Measurement*

4.3.2.1. The amplifier shall be operated under Standard Conditions of Measurement (Clause 3).

4.3.2.2. To verify the *rated* output power, an input signal at a level to produce the claimed rated output power shall be applied to the amplifier for a period of not less than 30 seconds, and the level of harmonic distortion shall then be measured (using the procedure of Clause 4.1.2.2.) to ensure that its value does not exceed that claimed by the manufacturer.

4.3.2.3. If it is desired to measure the *actual* output power (which will usually differ from the *rated* output power) the input voltage applied to the amplifier shall be increased until the level of harmonic distortion claimed by the manufacturer (as measured in Clause 4.1.2.2.) is produced in the voltage across the stated load resistance. The power in the load is then measured or is calculated from the measurement of the voltage across the load resistance, using the formula:—

$$P = \frac{E^2}{R}$$

Where P = Power output in watts
E = rms voltage across load in volts
R = Resistance of the load in ohms

This power is the *actual* power output of the amplifier under test.

4.4. **Maximum Permissible Input Voltage** (of a Pre-amplifier or Integrated Amplifier)

4.4.1. *Definition*

The maximum permissible input voltage is the highest value of input voltage which may be applied to an amplifier without causing the harmonic distortion claimed by the manufacturer to be exceeded.

NOTE: The main application of this characteristic is to amplifiers in which the gain control does not vary the input to the early stage(s) of the amplifier. If the amplifier incorporates a pre-set gain control operating on an intermediate stage, data on its operation should be provided.

4.4.2. *Method of Measurement*

4.4.2.1. The amplifier shall be operated under Standard Conditions of Measurement (Clause 3), except as stated below.

4.4.2.2. The equipment for verifying rated output voltage or power, as appropriate, shall be set up and adjusted as in Clause 4.2.2.2. or 4.3.2.2. The gain control is then adjusted until the output falls to one-quarter of the rated level, and the amplitude of the input signal is increased until the percentage of harmonic distortion in the output reaches that claimed by the manufacturer for the rated output level.

This procedure is repeated in convenient steps, until the percentage of harmonic distortion in the output cannot be reduced below the claimed value by a further adjustment of the gain control.

The voltage of this final input signal is the maximum permitted input voltage for the particular input socket employed.

4.5. **Sensitivity**

4.5.1. *Definition*

The sensitivity of an amplifier shall mean the Input Voltage Level, in millivolts or volts, which, when applied to the input terminals of an amplifier operating under Standard Conditions of Measurement (Clause 3), will develop the rated output voltage across the load of a pre-amplifier or rated output power across the load of a power or integrated amplifier.

4.5.2. *Method of Measurement*

4.5.2.1. The amplifier shall be operated under Standard Conditions of Measurement (Clause 3).

4.5.2.2. To each input in turn, an input signal is applied and adjusted to develop rated output voltage or power; the voltage of this signal is the sensitivity for the input being used.

4.5.2.3. The sensitivities at the various inputs of an amplifier shall be expressed by a tabulation of the values obtained in Clause 4.5.2.2.

4.6. Frequency Response Characteristic

4.6.1. *Definition*

The frequency response characteristic is the curve showing the variation of gain with frequency relative to the gain at 1,000 cps.

4.6.2. *Method of Measurement*

4.6.2.1. The amplifier shall be operated under Standard Conditions of Measurement (Clause 3), except as stated below.

The results shall be plotted with the frequency as abscissa on a logarithmic scale and the variation of input voltage (in decibels) as the ordinate on an inverted linear scale with the input voltage at 1,000 cps as 0 db.

4.6.2.2. *Pre-amplifiers*

4.6.2.2.1. *Level Position*

Measurements shall be taken with a signal applied to each uncorrected input socket in turn.

With the amplitude of the input signal being adjusted so that the amplifier output is maintained at the level of half the rated output voltage, the frequency of the input signal shall be varied between the limits of half the minimum to twice the maximum of the range of frequencies over which the manufacturer claims a level response (within ± 1 db).

Measurements of the input voltage shall be taken at sufficient intermediate frequencies (including 1,000 cps) to enable the characteristic curve to be plotted.

4.6.2.2.2. *Equalised inputs or equalisation selector switch*

With all other tone and filter controls at their "level" position, the procedure of Clause 4.6.2.2.1. shall be repeated for each equalised input or each position of the selector switch.

4.6.2.2.3. *Gain control*

With all tone and filter controls set at their "level" position, the procedure of Clause 4.6.2.2.1. shall be repeated, but with the input signal applied only to the least sensitive uncorrected input, and with the gain control at a setting to give a further 6 db attenuation at 1,000 cps (i.e., an output of one quarter of rated output voltage). This level of output is maintained over the same frequency range as in Clause 4.6.2.2.1. by varying the level of the input signal.

4.6.2.2.4. *Bass control*

With all other tone and filter controls set at their "level" position, the procedure of Clause 4.6.2.2.1. shall be repeated, firstly with the bass-control in its full "boost" position and then in its full "cut" position, but for the least sensitive uncorrected input only.

4.6.2.2.5. *Treble control*

With all other tone and filter controls set at their "level" position, the procedure of Clause 4.6.2.2.1. shall be repeated, firstly with the treble control in its full "boost" position and then in its full "cut" position, but for the least sensitive uncorrected input only.

4.6.2.2.6. *Filter controls,* treble and "rumble" (where fitted).

With all other tone controls set at their "level" position, the procedure of Clause 4.6.2.2.1. shall be repeated for each position of the filter control(s), but for the least sensitive uncorrected input only.

4.6.2.3. *Power amplifiers*

With the amplitude of the input signal being adjusted so that the amplifier output is maintained at the level of one-quarter of the rated output power, the frequency of the input signal shall be varied between the limits of half the minimum to twice the maximum of the range of frequencies over which the manufacturer claims a level response (within ± 1 db). Measurements of the input voltage shall be taken at sufficient intermediate frequencies (including 1,000 cps) to enable the characteristic curve to be plotted.

The procedure shall then be repeated, with the amplitude of the input signal being adjusted to maintain the full rated output power over either (*a*) the same frequency range or (*b*) between the frequency limits which require a 20 db increase in the input voltage over that needed to produce the rated output voltage at 1,000 cps, whichever is the smaller range.

4.6.2.4. *Integrated amplifiers*

With integrated amplifiers the procedures of Clause 4.6.2.2. shall be employed, but the value of the input signal shall be set to maintain an output level of firstly one-quarter and secondly the full rated output power, as in Clause 4.6.2.3.

4.7. Intermodulation Distortion

4.7.1. *Definition*

Intermodulation distortion is that part of non-linearity distortion consisting of sinusoidal components (intermodulation products) whose frequencies are sum and difference combinations of the fundamental and harmonic frequencies of the sinusoidal components of the complex excitation.

4.7.2. *Method of measurement*
The study of measuring and expressing intermodulation distortion has not reached a stage when a standard method can be recommended which would be suitable for all types of audio amplifiers. If intermodulation distortion tests are made, the method used should be stated with the results.

4.8. Hum and Noise

4.8.1. *Definition*
Hum and noise shall mean all voltage components delivered to its load by an amplifier operating with no input signal applied.

4.8.2. *Method of measurement*
The amplifier shall be operated under the Standard Conditions of Measurement (Clause 3), except as stated below.
Hum and noise voltages shall be measured with an instrument which has full-wave rectifying characteristics, responds to the average value and is calibrated to indicate the rms value of a sinusoidal waveform.
Measurements should preferably be taken both with and without a weighting network between the amplifier output and the input to the measuring instrument; when a weighting network is used its characteristics should comply with those recommended by the International Electrotechnical Commission, as given in curve A of IEC publication No. 123—Recommendations for Sound Level Meters.

4.8.2.1. *Pre-amplifiers*

4.8.2.1.1. A test signal at 100 cps shall be applied to a low level input (RIAA, if provided) and its amplitude adjusted to produce the rated output voltage.
The input signal voltage shall be measured and recorded.
NOTE: Equivalent RIAA characteristics are given in British Standard Specification No. 1928 : 1961—Gramophone Records and Reproducing Equipment.
The test signal shall then be removed and the input shunted by a non-inductive screened resistor of 47,000 ohms, unless the input is of low impedance, when the value of the resistor shall equal the source impedance specified by the manufacturer.
The output voltage shall be measured and recorded.

4.8.2.1.2. The equivalent hum and noise signal input voltage is then calculated from the formula:—

$$E_{\text{equiv.}} = \frac{\text{Hum and noise output voltage}}{\text{Signal output voltage}} \times \text{Signal input voltage}$$

4.8.2.1.3. The procedure of 4.8.2.1.1. and 4.8.2.1.2. shall be repeated with the same amplitude of test signal but with the gain control adjusted to give half the rated output voltage.
Each value of equivalent hum and noise signal input shall be expressed separately.

4.8.2.2. *Power amplifiers*

4.8.2.2.1. The input shall be shunted by a non-inductive screened resistor of 47,000 ohms, unless the input is of low impedance, when the value of the resistor shall equal the source impedance specified by the manufacturer.
The power at the output shall then be measured or calculated.

4.8.2.2.2. The hum and noise level in decibels is then calculated from the expression:—

$$10 \log_{10} \frac{\text{Output power with input shunted}}{\text{Rated output power}}$$

4.8.2.3. *Integrated amplifiers*
For integrated amplifiers the procedure of Clause 4.8.2.1. shall be followed, except that the output voltage used in the calculations shall be determined for (i) rated output power and (ii) one-quarter rated output power.

4.9. Damping Factor (Power amplifiers and integrated amplifiers)

4.9.1. *Definition*
Damping factor is the ratio of the rated load impedance to the internal impedance of the amplifier.

4.9.2. *Method of measurement*

4.9.2.1. The amplifier shall be measured under Standard Conditions of Measurement (Clause 3), except as stated below.

4.9.2.2. A 50 cps signal of amplitude to produce one-quarter of the rated output power in the rated load resistance shall be applied to the input.
The voltage across the output shall be measured and recorded.

4.9.2.3. Without adjusting the input the load is removed and the open-circuit output voltage shall be measured and recorded.

4.9.2.4. The damping factor is calculated from the formula:—

$$DF = \frac{V_2}{V_1 - V_2}$$

where DF is the damping factor and V_1 and V_2 are the no-load and on-load voltages respectively obtained in Clauses 4.9.2.3 and 4.9.2.2.

4.10. Stability (power amplifiers and integrated amplifiers only)

4.10.1. *Definition*
Stability is the ability of an amplifier to operate without the generation of spurious oscillations when used with a capacitive load.

4.10.2. *Method of Test*

4.10.2.1. The amplifier shall be measured under Standard Conditions of Measurement (Clause 3), except as stated below.

4.10.2.2. The amplifier shall be operated with a capacitor connected across any output, with no other load.

If the amplifier is claimed to be unconditionally stable, the test shall be made with a range of capacitor values, in steps of 0.01 μf from 0.01 μf to 0.1 μf, and in steps of 0.1 μf from μf to 1.0 μf.

If no special claims for stability are made, the value of the capacitor shall be such that its reactance at 200 Kc is equal to the nominal impedance of the output being used (e.g. 0.05 μf approx. for 15 ohms output). This condition of operation simulates conditions of capacitive loading which are not likely to be exceeded in domestic installations.

4.10.2.3. With a wide-band oscilloscope connected to the output, the trace shall be examined for evidence of spurious oscillation under the two conditions (i) no input to the amplifier and (ii) with a continuous sine wave input signal of constant amplitude which is swept over the frequency range of 10 cps to 70 cps; the amplitude of this signal shall be equal to the sensitivity voltage at 1,000 cps. If no spurious oscillation is found, the amplifier shall be deemed to be stable for that particular condition of operation.

4.11. Cross-Talk

4.11.1. *Definition*

Cross-talk shall mean all voltage components delivered to the load of one channel amplifier by the other channel amplifier in a stereophonic arrangement.

4.11.2. *Method of measurement* (Pre-amplifiers, Power amplifiers and Integrated amplifiers)

4.11.2.1. The amplifier shall be measured under Standard Conditions of Measurement (Clause 3), except as stated below.

4.11.2.2. Cross-talk voltages shall be measured with an instrument which is calibrated to indicate the rms value of a sinusoidal waveform, and which is fed from a high-pass filter with a cut-off frequency of 100 cps.

4.11.2.3. The output of each amplifier shall be connected to the stated load resistance specified by the manufacturer.

4.11.2.4. A test signal at 200 cps and amplitude equal to the sensitivity voltage at 1,000 cps shall be applied to a low level input socket (RIAA if provided) of one amplifier, and the output voltage from this amplifier shall be measured and recorded.

4.11.2.5. The corresponding input of the second amplifier shall be shunted with a non-inductive screened resistor of 47,000 ohms, unless the input is of low impedance, when the resistor shall equal the source impedance specified by the manufacturer: no signal shall be applied to this amplifier.

Any voltages across the output of this second amplifier shall be measured and recorded.

4.11.2.6. The cross-talk level in decibels is then calculated, using the formula:—

$$\text{Cross-talk (db)} = 20 \log_{10} \frac{\text{Cross-talk output voltage (Clause 4.11.2.5.)}}{\text{Signal output voltage (Clause 4.11.2.4.)}}$$

4.11.2.7. The measurements shall then be repeated with the frequency of the input signal being 5,000 cps, at the same level as in Clause 4.11.2.4.

4.11.2.8. The procedure of Clauses 4.11.2.4. to 4.11.2.7. shall be repeated, but with the function of each amplifier reversed.

4.11.2.9. The numerically lowest of the four results obtained in Clause 4.11.2.6. shall be specified as the cross-talk performance of the amplifier at its rated output.

4.11.2.10 The procedure of Clauses 4.11.2.4. to 4.11.2.8. shall be repeated, but with the level of the test signal equal to the value which would be required to produce one-quarter of the rated output power (half-rated output voltage) at 1,000 cps.

4.11.2.11. The numerically lowest of these four results obtained from Clause 4.11.2.6. shall be specified as the cross-talk performance of the amplifier at one-quarter of its rated output.

4.12. Transient Response

None of the methods currently used to determine transient response is thought to be comprehensive enough to cover all transients, and it is not considered possible to specify such a method at this time. However, transient response is covered to some extent by the requirements under frequency response, Clause 4.6.

If transient response tests are made, the method used, including measuring frequency, rise-time and overshoot, should be given with the results.

4.13. Power Consumption and Current Drain

4.13.1. *Method of measurement*

The consumption in volt-amperes should be determined under test conditions as specified in Clause 3, both with the equipment delivering its rated output and with no signal applied. If there are separate LT and HT battery supplies, the current consumed from each shall be measured.

4.14. Magnetic Radiation

Where claims in respect of low magnetic radiation are made, the magnetic field should be measured and expressed in gauss at a distance of one foot (30 cm) from the source(s) of radiation.

SINGLE-SIDEBAND

by B. J. Simpson

There has been a great growth of interest in single-sideband transmission over recent years, especially since amateur operators started using this method. Several readers have asked us for a short note describing this method of transmission, so here it is. "Ham" operators and others already using SSB will not learn anything from this, but it is intended to tell other readers just what is going on.

Let us state at the outset that there is nothing inherently new in SSB operation, because it has been in use for many years by commercial telephone companies and similar concerns. The main reason for the use of this technique in the first place was that the same information can be transmitted over a smaller band-width by using SSB than by the more conventional AM system. Consequently we have seen a condition over recent years where the ever-increasing demands upon space in the radio frequency spectrum has caused the increasing introduction of space-saving techniques.

Amplitude Modulation

An SSB signal is essentially a modified amplitude-modulated carrier, so that in order to present a clear picture, it is necessary first of all to review the AM system. Let us start with a radio transmitter with no modulation. This gives us what is known as the carrier, or the medium which is to carry the intelligence that we wish to send. When we tune a receiver to an unmodulated carrier, we hear a characteristic "hiss", but as yet no communication.

We are familiar with three ways of making our carrier carry the signal we wish to transmit, by varying the amplitude of the transmitted carrier. The three methods are generally described by the terms "interrupted carrier wave" (ICW), carrier wave (CW), and telephony. The first two methods involve coding of the message, whilst the third allows us to transmit coherent speech and music.

Reverting to our receiver tuned to an unmodulated carrier, if now an audio tone is used to vary the output amplitude of the transmitter, then that tone will be heard at the receiver. Thus in CW transmission, the coded signal is sent by modulating the carrier with tone bursts corresponding to the coded signal. At the receiver then is heard a series of dots and dashes also representative of the signal.

If the output of the transmitter is made to vary in amplitude, not by a single tone, but by a series of tones or frequencies, the output of the receiver will follow the input to the transmitter. This is merely the same thing as described in the foregoing paragraph in essence, and allows the transmission of intelligible speech and music.

The third method, ICW, involves complete switching of the carrier on or off, rather than variation of the amplitude by a wave train. The carrier is normally off, and is transmitted in bursts corresponding to the coded signal. This will produce nothing but a faint hiss in a normal receiver, and a modified receiver is therefore required for this method. The receiver is fitted with a beat-frequency oscillator (BFO) which continuously injects into the receiver a carrier having a frequency slightly different from that of the carrier we wish to receive. If the difference frequency is within the audio range, then tone output will result from the receiver when an ICW transmission is being received due to mixing of the two frequencies.

Side Bands

To carry the discussion further, we will for the time being concentrate on CW transmission, remembering that what is said will be applicable also to telephony. If the amplitude-modulated output of the carrier is analysed, presupposing a single audio tone applied to the carrier, the output of the transmitter contains in fact three frequencies. These are the carrier frequency, the lower side frequency and the upper side frequency.

This situation is illustrated in Fig. 1. This diagram shows the output of a transmitter having a carrier frequency of 1 megacycle, and modulated with a 1,000 cps tone, and may be described as a frequency-spectrum plot of the transmitter. It will be seen from the diagram that the upper and lower side frequencies consist respectively of the carrier frequency plus and minus the modulating frequency.

The situation as described, using a single modulating tone, is a simple one; the picture becomes more complex when the carrier is modulated with a complex wave consisting of many frequencies, as when music is being transmitted. In this case, bands of frequencies are formed above and below the carrier frequency. Each sideband contains all the modulating frequencies. It will be obvious that the instantaneous width of the sidebands will depend on the highest instantaneous modulating frequency. It will also be seen that the wider the range of frequencies it is desired to transmit, the wider the sidebands will be.

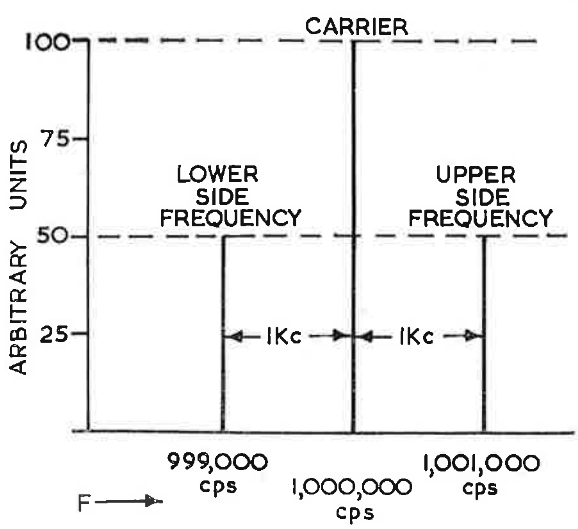


Fig. 1

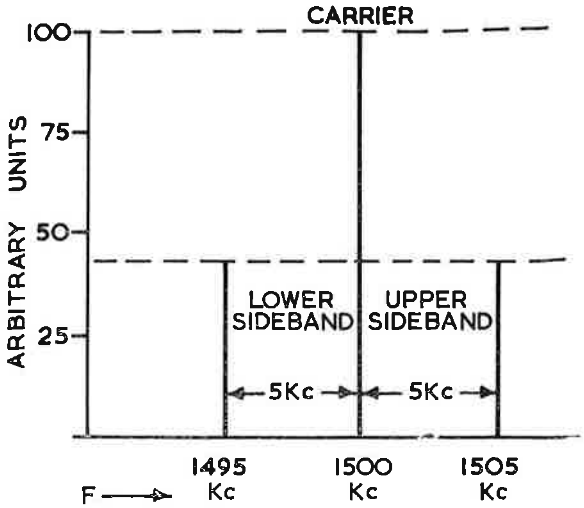


Fig. 2

An example of a transmitter frequency spectrum that could be applicable to a medium frequency broadcasting station is shown in Fig. 2. Here, with a carrier frequency of 1.5 Mc, and a highest modulating frequency of 5.0 Kc, the limits of the sidebands become 1495 Kc and 1505 Kc. In Australia, the nearest possible adjacent channel transmitter would be 10 Kc away from 1500 Kc, so that there is a limit on the highest permissible modulating frequency of about 9.8 Kc, assuming vacant adjacent channels. As most readers will be aware from listening tests, most stations never approach this figure, and maximum modulating frequencies appear to be much nearer 5 Kc.

Modulation Depth

The depth of modulation is determined by the relative amplitude of the unmodulated carrier and of the modulating frequency, and is expressed as a percentage of the carrier. When the two amplitudes are equal, 100% modulation is applied, and the carrier is reduced to zero at the negative peaks of the modulating signal. A further increase results in increasing periods during which the carrier is cut off altogether, and is an intolerable condition. In practice, the modulation is held as high as possible whilst avoiding the risk of going over the 100%.

In Fig. 1, the scale used indicates that the modulating signal is of an amplitude to cause 100% modulation, in which case the amplitudes of the upper and lower side frequencies are half that of the carrier. In Fig. 2 however, which is nearer to a typical case, less than 100% modulation is shown. The distribution of power in the sidebands is discussed later.

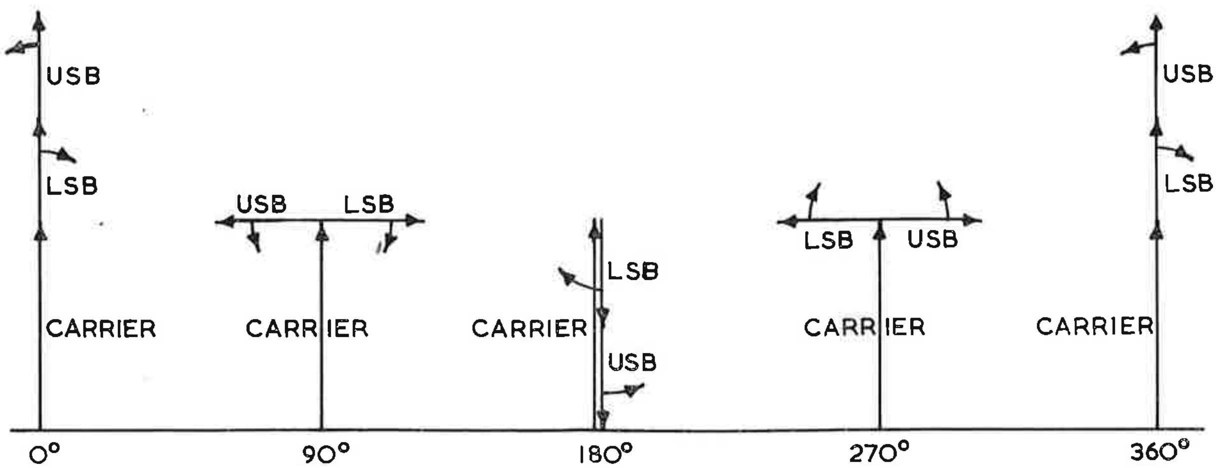


Fig. 3

Selectivity

The way in which a receiver responds to an amplitude-modulated wave depends among other things on the selectivity of the receiver. In order to receive intelligence, except with ICW transmissions, the receiver must respond not only to the carrier frequency, but also to the side or sideband frequencies, or at least to most of them.

In the case of Fig. 1 again, a receiver having a selectivity of ± 1 Kc or wider would receive the signal as a 1 Kc tone. If on the other hand a highly selective receiver with only a ± 250 cps response would receive no tone. Instead, the receiver would regard the carrier, and the two side frequencies, as three unmodulated carriers. The width of the sidebands and the receiver selectivity therefore control the frequency response of the system, but the wider the frequency response, the larger the space occupied in the frequency spectrum. This is the major difficulty in high-quality AM broadcasting.

Power in the Modulated Wave

When a carrier is 100% modulated by a single tone, the voltage of either side frequency will be exactly half that of the carrier. Assuming that the resistance of the circuit is constant at the frequencies of interest, power will be proportional to the square of the voltage. In our first example, the power in each of the two side frequencies will be $(0.5)^2$ times the carrier power. If the carrier power is 10 Kw, the power in each side frequency will therefore be 10,000 watts $\times$ 0.5^2, or 2.5 Kw. The total power in the two side frequencies will be 5 Kw, or half the carrier power of the transmitter.

In most introductory texts in this field, there appears a diagram which is intended to show the carrier frequency, the modulating frequency, and the resultant modulated wave. This type of diagram appears to show that the carrier amplitude varies during modulation, and so contradicts earlier statements that the carrier amplitude remains unchanged. The puzzle is resolved when it is remembered that the diagram shows a composite wave, consisting of two side frequencies and the carrier modulated by an audio frequency.

If we turn to Fig. 3 and study the action vectorially, a different type of picture emerges. The carrier is represented by a line of one unit in length, and the side frequencies by lines of half a unit in length. Because the lower side frequency is lower than the carrier frequency, its vector will appear to rotate clockwise with respect to the carrier. For the converse reason, the vector representing the upper side frequency will appear to rotate in a counter-clockwise direction.

At an instant arbitrarily chosen as zero degrees, the carrier and the two side frequencies add, giving an amplitude of two units. At one half of a modulating cycle later, the two side frequency vectors have rotated through 180 degrees, and the three voltages add to zero. A further half cycle later, the original position is restored, whilst at the 90 and 270 degree points, the vectors of the two side frequencies cancel, leaving only the carrier.

It will be seen therefore, that the value of the composite wave will vary from twice the carrier amplitude to zero. As a simplification, we can now see that our 10 Kw transmitter will have a peak power output at 100% modulation of 10 Kw $\times$ 2^2, or 40 Kw. This figure sets the peak modulation capability if the full output power of the transmitter at 100% modulation is to be realised without distortion.

Complex Side Bands

The existence of complex side bands when multiple tone modulation is used was mentioned earlier, but left over whilst other factors were mentioned. It is now necessary to revert to them, because they have certain characteristics that are not apparent from the simplified cases already mentioned.

When a wave is modulated, side bands are produced, two of them, one on either side of the carrier. The two side bands are identical in formation, except that as far as modulating frequencies are concerned, they lie back to back. As the highest modulating frequency is increased from zero, the side bands move progressively out from the carrier. This is perhaps an over-simplification, but gets the idea across. The two side bands occupy space in the radio spectrum. The unmodulated carrier occupies no space at all.

To deal with the formation of side bands, we will again start up our 10 Kw transmitter. This time, instead of using only one modulating frequency, we will use four together, 1 Kc, 2 Kc, 3 Kc and 4 Kc. To simplify the matter it will be assumed that the amplitudes of all four tones are

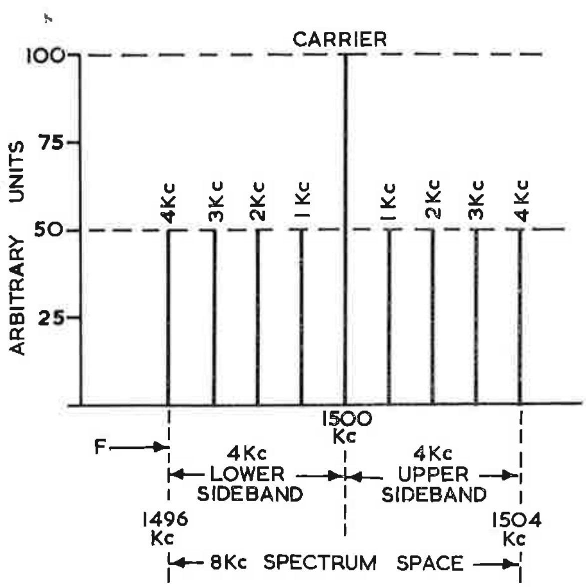


Fig. 4

the same and that they have no effect (cross modulation) on each other. The situation is then described by Fig. 4, where the condition indicates 100% modulation.

The symmetrical arrangement of the side bands as shown in this diagram hardly requires any explanation. We have already seen that the width of the side bands depends on the modulating frequency, increasing with frequency. Both side bands are produced at all times, so that the spectrum space occupied is twice one side band. It should also be noted that if the modulated wave is heterodyned to a different operating frequency, the sidebands are also heterodyned and preserve the same relationship to each other and the carrier.

Efficiency

The relative powers in the carrier and the two side bands were mentioned earlier. A class C plate modulated rf amplifier will have an efficiency of the order of 75 to 80%, this figure being derived from the rf power output in watts divided by the dc power input to the stage, also in watts. If we go back now to our 10 Kw transmitter, the dc input power could be, for 75% efficiency, 10 Kw divided by 0.75, or 13.333 Kw. The difference of 3.3 Kw represents a loss; it is dissipated in the circuit, mainly in the form of heat at the anodes and screens of the final stage.

How about the power in the sidebands? We saw that the total power (with single tone modulation) was 5 Kw in the two sidebands. Most of this power is supplied by the modulator circuits.

Single Sideband

So far we have seen that the intelligence in an amplitude modulated transmission is contained in the modulation itself, and that the carrier contributes nothing in this regard. We have also seen that the space occupied in the radio spectrum is determined by the extent of the side bands; the carrier occupies no space at all. There is also the fact that two side bands are produced, whereas all the required intelligence is available in one only. From this it follows that the removal of one of the sidebands and/or the carrier could result in a transmission occupying only half the previous space in the spectrum, with large economies in power required, but which would convey the same information.

The picture evoked here then, is of two additional methods of transmission based on the standard AM system. In one, both sidebands are retained but the carrier is removed; this is called double sideband (DSB). In the other, both the carrier and one of the sidebands are removed; this is called single sideband (SSB). The two arrangements are shown in Fig. 5, compared with conventional AM.

In part A of Fig. 5, we see the 10 Kw transmitter modulated with a 1 Kc tone, producing side frequencies of 1499 Kc and 1501 Kc. The carrier power is 10 Kw, and the power in each side frequency is 2.5 Kw. In all these examples, 100% modulation is presupposed. It will be remembered that the peak output power in our transmitter was 40 Kw, and that 3.3 Kw was lost in the 75% efficiency figure for the unit.

In part B of the diagram, the carrier has been suppressed or virtually removed. The removal of the carrier, with its high power dissipation, will allow us to raise the power in each side frequency to 5 Kw, making a total of 10 Kw now in the two side frequencies. The peak power rating will remain at 40 Kw. Because the intelligence we wish to transmit is contained in the side frequencies, and we have increased the power in them without increasing the plate dissipation of the final amplifier stage, we have a much more efficient system.

Turning now to part C of the diagram, here both the carrier and one of the sidebands have been suppressed. The power in the remaining side frequency may now be raised to 10 Kw without increased dissipation. Once again an improvement in efficiency has been made, without loss of intelligence, because the same information is contained in both side frequencies.

The removal of one of the side frequencies will halve the spectrum space required for the transmission, so that besides having a much more efficient system, the problem of finding space for the transmission is reduced. This is particularly the case where the sidebands are very wide, as for example in TV transmissions; single sideband is used in Australian TV stations for the vision transmission, where a bandwidth of the order of 5 Mc is required.

In the receiver, only half the former bandwidth is required to receive the transmission. Since noise is proportional to the bandwidth used, this

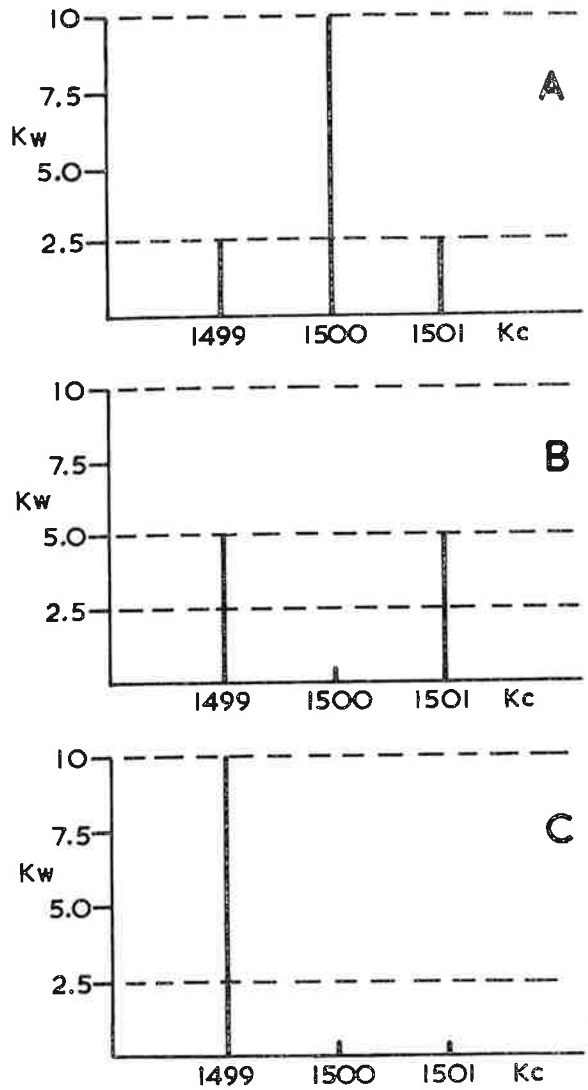


Fig. 5

results in an improvement in the signal/noise ratio of the SSB receiver as compared with a conventional AM receiver.

Now that we have covered the outline of what is done and why, it remains to be seen how this is achieved. This will be the subject of a continuation of this article in the next issue.

THE TRANSISTOR EQUIVALENT CIRCUIT

In the application of electron valves in high-frequency circuits, calculations and investigations are made by using four-pole parameters which can be represented by a π equivalent circuit. It has been shown that it is possible to develop an equivalent circuit for transistors which can be successfully employed to solve amplifier problems. This equivalent circuit is based on a pi-configuration, with an additional resistance, the extrinsic base resistance, in series.

In the application of such an equivalent circuit, it is essential to know to which physical process in the transistor the elements of the equivalent circuit are assigned. This article is intended to clarify the physical meaning of the equivalent circuit and to facilitate, at least qualitatively, estimations of how the elements vary when the construction of the transistor is modified, or different operating conditions (operating point, operating voltages) are selected.

The Transistor Equivalent Circuit

The equivalent circuit of the transistor is based on the common-emitter configuration. The elements, referring to Fig. 1, are:

- $r_{bb'}$ Extrinsic base resistance.
- $g_{b'e}$ Conductance between internal base point b' and emitter.
- $C_{b'e}$ Capacitance between internal base point b' and emitter (this is the barrier plus the diffusion capacitance).
- $g_{b'c}$ Conductance between internal base point b' and collector.
- $C_{b'c}$ Capacitance between internal base point b' and collector.
- g_{ce} Internal conductance between collector and emitter.
- C_{ce} Capacitance between collector and emitter.
- C_{cb} Capacitance between collector and base.

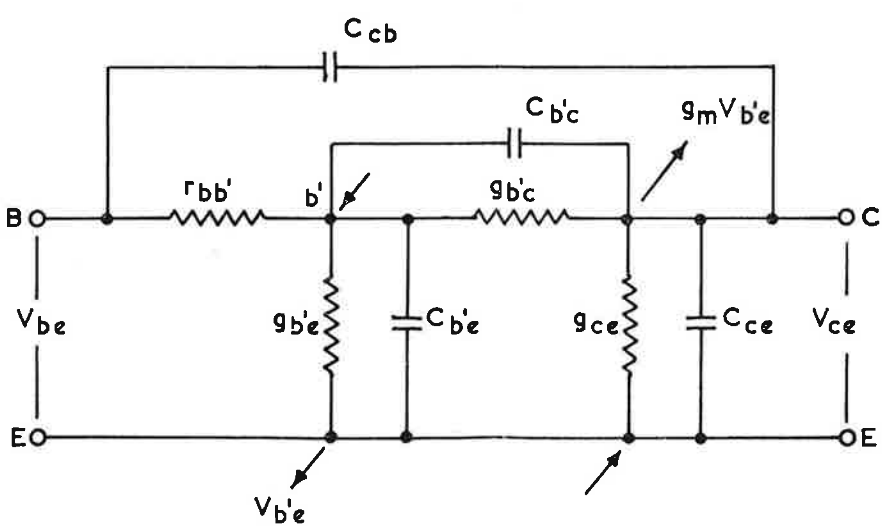


Fig. 1

PHYSICAL MEANING OF THE CIRCUIT ELEMENTS

Extrinsic Base Resistance

The extrinsic base resistance is given by the integral of all current paths between the emitter barrier and the base connection. (Fig. 2). The resistance which the current encounters while traversing the indium dot can be neglected, because indium is a metal, and as such a good conductor.

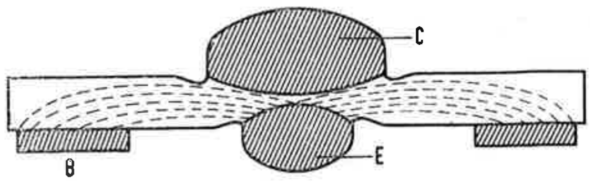


Fig. 2

The resistance of the p-layer is also small, as the layer is thin, and compared with the n-type germanium, is a good conductor. Refer to Fig. 3.

COMPARISON TABLE

Copper	0.017×10^{-4}	ohm-cm
Indium	0.09×10^{-4}	ohm-cm
p-Germanium*	0.02	ohm-cm
n-Germanium*	3.5	ohm-cm
Intrinsic germanium	48	ohm-cm

$^*p_p = 10^4.n_i$, $n_n = 20.n_i$ (typical values).

Therefore it is only necessary to consider the resistance of the base material because the specific resistivity of the n-germanium is relatively high. Further, the base region between the two alloy points is thin, i.e., there is only a small cross-section to conduct the current.

With high-frequency transistors a normal base resistance of approximately 100 ohms is encountered; with valves such a resistance in the grid connection does not exist.

Internal Control Conductance

The control conductance is determined by the emitter barrier and the current which flows through the control electrode during operation. For a numerical appreciation of its value, the relevant physics has to be considered.

DC Barrier (Diffusion) Potential

In the alloy process, an abrupt junction is produced between the p-type and the n-type areas. In the p-region (emitter), there exists a high hole density of $10^4.n_i$, and a low electron density of $10^{-4}.n_i$. In the n-region (base), there is a low hole density of $5.10^{-2}.n_i$ and a high electron density of $2.10.n_i$. Here the expression n_i represents the intrinsic number of electron-hole pairs in germanium at 300°K, which is 2.5×10^{13} per cubic centimetre.

Because of the different densities between the two regions, a barrier region is formed. Within this barrier a fall from one density to the other occurs, as illustrated in Fig. 4. Simultaneously, a diffusion potential build up at the barrier takes place. This potential is formed by the carrier charges of opposite polarity in the two regions. The charges of the carriers which have traversed the region and the charges of the ionized atoms left behind produce a field which opposes further exchange. The barrier is therefore also referred to as the space charge region.

In the absence of any external potential, a density distribution as shown in Fig. 5 is obtained. The barrier potential is 0.32 volts at the assumed density differences. When an external potential is applied between the base and emitter, this adds to the barrier potential, i.e., it is only effective at the barrier. The remaining p-type and n-type regions remain without a field.

As already mentioned, a potential is produced within the barrier region by the density gradient. This potential may be expressed as:

$$V_d = -V_T . \ln \frac{p_p}{p_n}$$

$$= -V_T . \ln \frac{n_n}{n_p} \quad \text{-----(1)}$$

This equation not only gives the barrier potential for a given density relation. It also permits the density ratio to be determined from a given barrier potential.

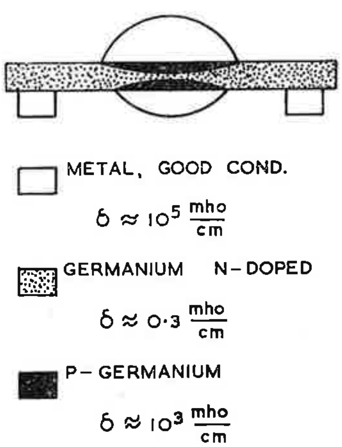


Fig. 3

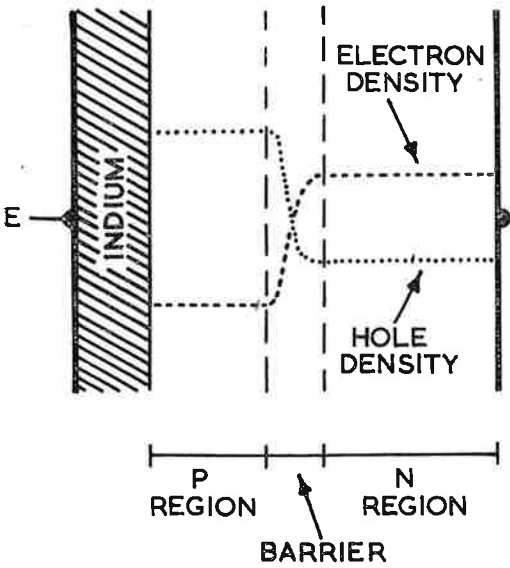


Fig. 4

Figures 6A, 6B and 6C show these relationships; Fig. 6A shows the condition without an external potential, Fig. 6B shows the effect of an external potential applied in the same polarity as the barrier potential, and Fig. 6C shows the effect of an external potential applied in opposite polarity to the barrier potential.

When the barrier potential and the external potential are of the same polarity, i.e., the emitter is biased negative with respect to the base, there is a decrease in the minority carrier densities. When the opposite alternative is true, there results an increase in minority carrier densities.

Consequently, with the application of an external potential, as shown in Figs. 6B and 6C, three points are of interest.

Firstly, a density at the barrier is produced which differs from the equilibrium density as determined by the physical properties of the junction.

Secondly, the value of the diffusion potential as determined in expression (1) is replaced by a potential V_B, so the ratio between majority carriers and minority carriers will change. This condition may be satisfied if (a) the majority carrier density changes with respect to the equilibrium density and the minority carrier density remains the same as the equilibrium density, or (b) the minority carrier density changes and the majority carrier density retains its equilibrium value.

The latter case predominates because in a crystal, the positive and negative charge carriers have a sum equal to zero. A change in the minority carrier density n_p by, say, a factor of 2 will not appreciably affect the potential ratios as the density is small. However, a change in the majority carrier density p_p by the same factor will because of its large value, produce extraordinarily high space charges between the majority carriers and the ionized atoms, and also a strong electric field.

Thirdly, with an external potential V, equation (1) becomes:

$$V_B = V_d + V$$
$$= -V_T \cdot \ln \frac{p_p}{p}$$
$$= -V_T \cdot \ln \frac{n_n}{n} \quad \text{----(1a)}$$

n and p being the minority carrier densities at the barrier region.

Because at the external borders of the barrier layer the density has to correspond to the equilibrium state (this condition is always valid for a so-called "ohmic metal/semiconductor contact") a decreasing or increasing density, depending on the polarity of V, must exist from p to p_n and from n to n_p. Apart from distortions, this density fall is linear, hence the term "diffusion triangle".

Diffusion Current

Because of the diffusion fall across the barrier, dc diffusion currents will flow through it.

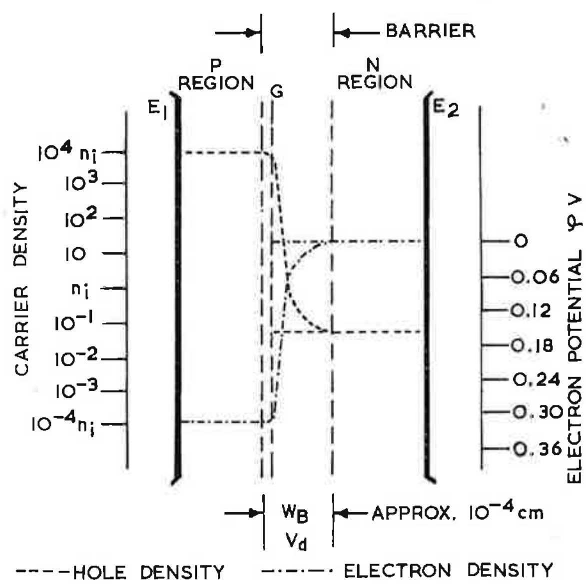


Fig. 5

$$I_n = \frac{q \cdot \mu_n \cdot V_T(n - n_p)}{w_p}$$

$$I_p = \frac{q \cdot \mu_p \cdot V_T(p - p_n)}{w_n} \text{ ----(2)}$$

where:
I_n is the electron current density
I_p is the hole density
q is the element charge
μ_n, μ_p are the mobility of the charge carriers
V_T is the thermal voltage, equal to k.T/q (25 mv at 300°K).
w_n, w_p are the width of the barrier regions
$n-n_p$, $p-p_n$ are the differences of the densities at the beginning and the end of the diffusion triangle. As $p-p_n$ is greater than $n-n_p$, I_p is prevalent in the normal case.

Comparing the expressions (1a) and (2), gives the law of characteristic curves for a semiconductor.

$$I = I_B . e^{V/V_T} - I_B$$

Normally,

$$I_B . e^{V/V_T} > I_B$$

and therefore

$$I \approx I_B . e^{V/V_T}$$

From this the emitter conductance can now be determined:

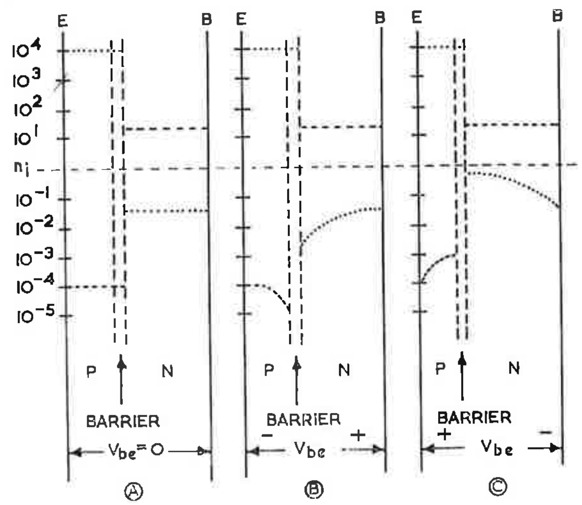


Fig. 6

$$g_e = \frac{dI_E}{dV} = \frac{I_B . e^{V/V_T}}{V_T}$$

$$= \frac{I_E}{V_T} = 39\, I_E$$

$$g_e \approx \frac{I_E(ma)}{25} = \frac{1}{r_e}$$

where r_e is called the emitter or emission resistance (ac resistance), and its value is inversely proportional to the dc emitter current.

Only a fraction of the hole current coming from the emitter flows out of the base. This fraction is fixed and determined by the recombination in the base layer. Let

$$\frac{\Delta I_c}{\Delta I_b} = \alpha'_o$$

then the base conductance $g_{b'e}$ can be eliminated from the emitter conductance or emitter resistance r_e.

$$g_{b'e} = \frac{I_E}{25} \cdot \frac{1}{\alpha'_o}$$

$$= \frac{1}{r_e . \alpha'_o}$$

In the same way as the input resistance of a class C operated valve can be determined from the control voltage and the grid current, so in this case $g_{b'e}$ is determined by V and I_e. Notice, however, that $g_{b'e}$ by itself does not give the input conductance of the transistor because it has $r_{bb'}$ in series.

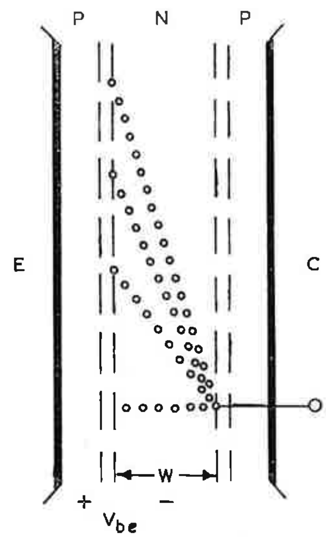
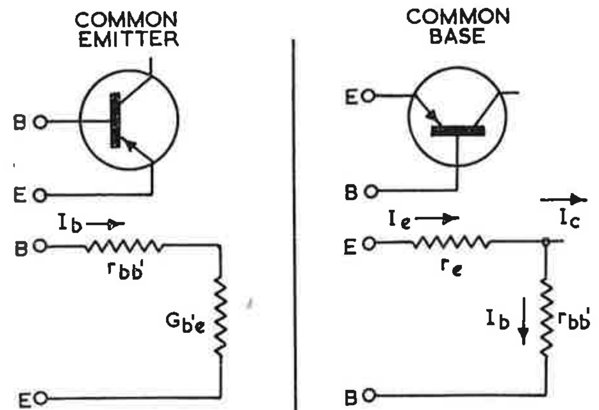


Fig. 7



$$V_{be} = I_b \cdot r_{bb'} + I_b \cdot \frac{1}{G_{b'e}}$$

$$r_{be} = \frac{V_{be}}{I_b} = r_{bb'} + \frac{1}{G_{b'e}}$$

$$r_{be} = r_{bb'} + \alpha' \cdot r_e$$

$$V_{eb} = I_e \cdot r_e + I_b \cdot r_b = I_e \cdot r_e + \frac{I_e}{\alpha'} \cdot r_b$$

$$r_{eb} = \frac{V_{eb}}{I_e} = r_e + \frac{r_{bb'}}{\alpha'}$$

Fig. 8

Diffusion Capacitance

A change in control voltage causes a change in the carrier density at the emitter barrier, see Fig. 7. With it varies the density gradient and consequently the size of the diffusion triangle and its charge content. This means that carrier charges have to diffuse into or out of the region.

The comparison with a capacitance is obvious. The same situation applies because a change in potential causes carrier charges to flow into or out of the region until a charge equilibrium is reached.

$$C_D = \frac{w^2}{2D \cdot r_e} \approx C_{b'e}$$

where w is the width of the base layer, and D is the diffusion constant of carrier charges. The diffusion capacitance depends therefore on the width of the base layer and on r_e, i.e., on the dc current I_E.

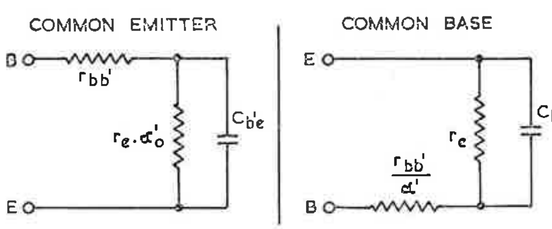
Cutoff Frequencies

Cutoff frequencies apply to transistors, and are determined by the parameters $r_{bb'}$, $g_{b'e}$ and $C_{b'e}$ in the input circuit. Fig. 8 shows the comparison between the input circuit of a common emitter and a common base configuration, so that the input resistance for both circuits may be obtained simultaneously. The cutoff frequencies may be obtained from the resistances and capacitances shown in Fig. 9.

In case A of Fig. 9, there is shown a current source with high internal resistance, and in which cutoff frequencies of α and α' apply respectively to the two circuits. In this case the resistance $r_{bb'}$ or $r_{bb'}/\alpha'$ respectively may be neglected. For the determination of the alpha cutoff frequency, which is the frequency at which alpha falls to 0.71 of the low-frequency value, only the two parallel branches have to be considered.

The equivalent circuit gives adequate accuracy only for a limited frequency range, approximately up to the alpha cutoff frequency. The result is that the cutoff frequency for the common base connection is higher by the factor α' than the alpha cutoff frequency for the common emitter connection.

In case B of Fig. 9, there is shown a voltage source with low internal resistance. The g_m cutoff frequency can be calculated in the same way by assuming a source of low internal resistance. This means that the series branches $r_{bb'}$ or $r_{bb'}/\alpha$ respectively can no longer be neglected. The g_m cutoff frequency (where the mutual conductance has fallen to 0.71 of the low-frequency value) is equal to the alpha cutoff frequency multiplied by the factor $r_e/r_{bb'}$. The g_m cutoff frequency is therefore noticeably affected by the extrinsic base resistance.



[A] CURRENT SOURCE ($R_i = \infty$)
α CUTOFF FREQUENCY

$$\omega_{\alpha'} = \frac{1}{C_{be} \cdot r_e \cdot \alpha'_o} = \frac{2d}{w^2 \cdot \alpha'_o} \qquad \omega_{\alpha} = \frac{1}{r_e \cdot C_{b'e}} = \frac{2d}{w^2}$$

[B] VOLTAGE SOURCE ($R_i = 0$)
g_m CUTOFF FREQ.

$$\left[r_e \cdot \alpha'_o \gg \frac{1}{\omega C_{be}} \right] \qquad \alpha' = \frac{1}{\omega C_{be} \cdot r_e}$$

$$\omega_{g'm} = \frac{1}{r_{bb'} \cdot C_{b'e}} = \frac{r_e}{r_{bb'}} \cdot \omega_{gr}^{(\alpha)} \qquad \omega_{gm} = \frac{r_e}{r_{bb'}} \cdot \omega_{gr}^{(\alpha)}$$

Fig. 9

Feedback Capacitance

The transistor feedback capacitance C_{ce} corresponds to the grid/plate capacitance C_{gp} in a valve. C_{ce} arises from the fact that just as in the base to emitter case, a barrier is also formed between the base and the collector, shown in Fig. 10. At the borders we find regions of different carrier charge densities.

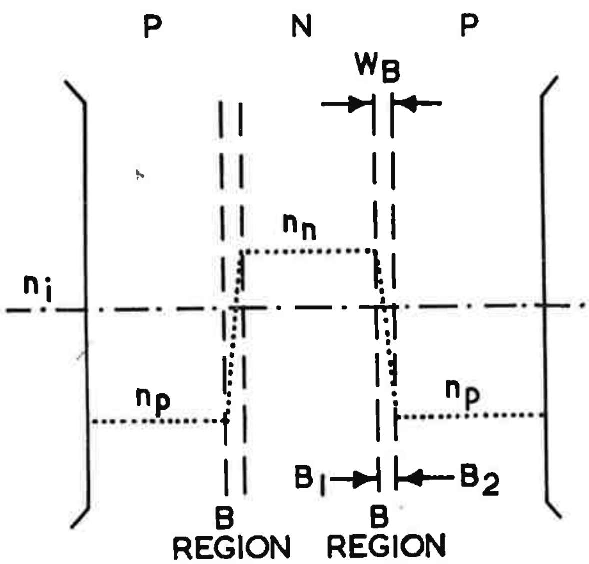
Now the electron density fall is identical with that of the potential. Therefore only the electron density is shown. At the borders B1 and B2 of the barrier region between base and collector, we have different electron densities, i.e., different potentials. Within the barrier there is a potential drop, which is linear to a first approximation.

This barrier is also a capacitor, the value of which is given by:

$$C = \frac{\varepsilon . F}{W_B}$$

$$W_B = 4.3 \times 10^3 \sqrt{V_B / n_n}$$

where W_B is the width of the barrier, V_B is the potential at the barrier, which is equal to the sum of the barrier potential and the external potential, and n_n is the majority carrier density in the base material, given by its equilibrium impurity content.



$$C = \frac{\varepsilon . F}{W_B}$$

$$W_B = 4.3 \times 10^3 \times \sqrt{\frac{V_B}{n_n}}$$

Fig. 10

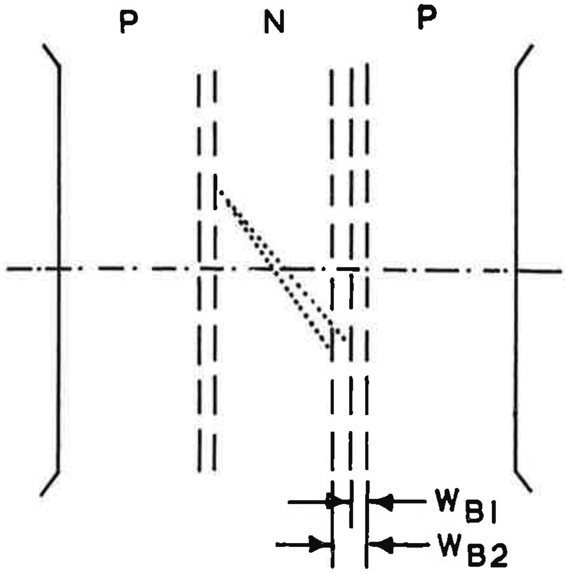


Fig. 11

An important factor to consider is that the barrier capacitance depends on the applied voltage. The effect of the ac signal voltage is usually not critical as these voltages are small compared with the operating voltage.

As shown in Fig. 11, a change of V_B causes a change in the base length of the diffusion triangle, i.e., of the triangle area. This of course also alters its charge content. Because the potential at the barrier has to remain constant, the charge and discharge of the diffusion triangle has to take place through the collector barrier.

The capacitance between collector and base therefore consists of two parts. These are the capacitance of the opposing borders of the two regions, the barrier capacitance, and the capacitance caused by the variation of the diffusion triangle.

Feedback Conductance

The presence of the conductance g_{ce} is demonstrated in Fig. 12. Assume that an increase in collector potential has pushed the base/collector barrier towards the base. The diffusion triangle in the base region will become smaller, and the diffusion flow will become greater.

Under this condition, I_C will increase. This current increase has two component parts, I_{C1} and I_{C2}. The former is caused by the greater diffusion flow; the emitter current will increase by the same amount, as mentioned in the discussion on internal resistance. The second component I_{C2} comes about in this way. Recombination in the smaller

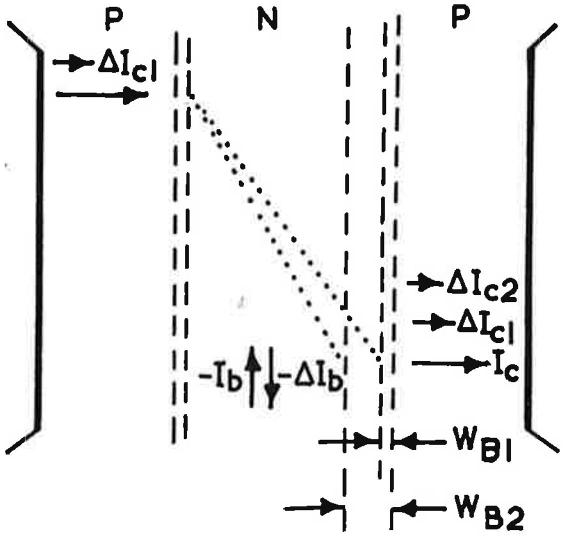


Fig. 12

diffusion triangle is reduced. The base current decreases by ΔI_B and the collector current increases by the same amount (ΔI_{C2}) because fewer holes recombine in the base region. Since ΔI_B (electron conduction) flows in the opposite direction to ΔI_{C2} (hole conduction), a closed circuit for the current is produced. The feedback conductance g_{ce} is therefore given by $\Delta I_{C2}/\Delta V_C$.

Internal Resistance

As already mentioned, an increase of V_{CE} will result in an increase not only of I_C but also I_E. Therefore V_C will affect I_E. The internal resistance is therefore expressed by $\Delta I_{C1} = \Delta I_E$.

Collector/Emitter Capacitance

This capacitance is mainly determined by the wiring and transistor leads. The emitter-to-collector interelectrode capacitance is minute because the base layer can be considered as being without fields. The lines of field originating at the collector and emitter terminate in the base as in any good-conducting metal surface.

The screen grid of a valve operates in the same way. It prevents the penetration of lines of field from the plate to the cathode.

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Editor .... **Bernard J. Simpson**

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